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MARKOV Model Application to Proliferation Risk Reduction of an Advanced Nuclear System

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MARKOV MODEL APPLICATION TO PROLIFERATION RISK REDUCTION OF AN ADVANCED NUCLEAR SYSTEM

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ABSTRACT

The Generation IV International Forum (GIF) emphasizes proliferation resistance and physical protection (PR&PP) as a main goal for future nuclear energy systems. The GIF PR&PP Working Group has developed a methodology for the evaluation of these systems. As an application of the methodology, a Markov model has been developed for the evaluation of proliferation resistance and is demonstrated for a hypothetical Example Sodium Fast Reactor (ESFR) system. This paper presents the case of diversion by the facility owner/operator to obtain material that could be used in a nuclear weapon. The Markov model is applied to evaluate material diversion strategies. The following features of the Markov model are presented here: (1) An effective detection rate has been introduced to account for the implementation of multiple safeguards approaches at a given strategic point; (2) Technical failure to divert material is modeled as intrinsic barriers related to the design of the facility or the properties of the material in the facility; and (3) Concealment to defeat or degrade the performance of safeguards is recognized in the Markov model. Three proliferation risk measures are calculated directly by the Markov model: the detection probability, technical failure probability, and proliferation time. The material type is indicated by an index that is based on the quality of material diverted. Sensitivity cases have been done to demonstrate the effects of different modeling features on the measures of proliferation resistance.

INTRODUCTION

The Generation IV International Forum (GIF) emphasizes proliferation resistance and physical protection (PR&PP) as a main goal for future nuclear energy systems. The PR&PP Working Group of GIF has developed a pathway based methodology for the evaluation of these systems [1]. As an application of the methodology, a Markov model implementation of the methodology has been developed for the evaluation of the PR&PP characteristics [2] and demonstrated for different nuclear energy systems and scenarios [2-5].

The Markov process consists of a set of random variables whose future and past states are independent given the present states. The possible values of these random variables constitute the state space. Markov processes are usually described by a directed graph, with edges characterized by transition parameters from one state to another state. Therefore, the Markov approach is a suitable tool for pathway analysis for PR&PP evaluation.

The paper is organized as follows: the next section briefly discusses an adaptation of the Markov approach to the proliferation study, the system features that are expected to have significant impacts on Markov model parameters and need to be considered and proliferation resistance measures that can be calculated. Major system elements including elements of the ESFR recycle facility are identified in the third section. Material flows and stocks and a Markov model of the entire ESFR system are also shown in the section. In the fourth section, diversion scenarios associated with individual system elements of the ESFR system are evaluated by calculating both probabilistic and deterministic proliferation resistance measures. Proliferation success probabilities of diversion scenarios are graphically presented using a bar diagram. Conclusions and future work are discussed in the last section.

ADAPTING THE MARKOV MODEL APPROACH TO THE PROLIFERATION RESISTANCE STUDY

In applying the Markov approach to the proliferation study of nuclear energy systems, the normal flow of nuclear material in the fuel cycle (e.g., front and back ends) are accounted for and the abnormal flow due to proliferation activities are modeled as a time dependent random process. Major activity modules in the fuel cycle (e.g., a physical process in a recycle facility) and the proliferation pathway (e.g., the act of diversion from a declared facility) are represented by a number of discrete stages in the Markov chain. In addition, absorbing states (terminal stages) are used to represent the effective termination of the proliferation activity due to intrinsic (e.g., radiation) or extrinsic (e.g., international safeguards) barriers. The transition between stages is treated as a random process with a given probability distribution. The transition rate is characterized by time parameters that are based on physical processes.

A Markov model of the nuclear energy system consists of a number of states with transitions characterized by time parameters that are physically meaningful. Therefore, all the features of the system that have impacts on transition parameters of the Markov model should be considered accordingly. Effectively, the modeled features affect the dynamic properties of the Markov model. In particular the following features have been included in the Markov model:

1) An effective detection rate is introduced to account for the implementation of multiple safeguards approaches at a given strategic point. Uncertainties related to the accuracy/sensitivity of measurement methods are also considered in the model. The potential for false alarm due to over-sensitivity of safeguards equipment is accounted for by a parameter, the confidence level of diversion confirmation;
2) A state called "diversion failure" is introduced to reflect the inability of the proliferator to overcome the intrinsic barriers originated from either the design of the facility or the properties of the material in the facility;
3) Concealment to defeat or degrade the performance of safeguards is implemented in the Markov model. It is considered as a tactic of the proliferator and is assumed to prompt more immediate and concerted responses from the safeguards inspectors;
4) Human performance in the safeguards area is incorporated in the Markov model by modifying the time parameter of a human action (e.g. the transition time associated with an inspection) with a success factor that takes into consideration the probability of human errors.

Details of mathematically formulating extrinsic barriers, intrinsic barriers, concealment, and human factors have been discussed in [2] and will not be discussed further in this paper. Example studies have been done to demonstrate the effects of different features on the PR measures for the fuel facility of the ESFR system [2-5]. Sensitivity cases have been done to demonstrate the effects of different modeling features on the measures of proliferation resistance.

Of the six PR measures [1] developed by the PR&PP Working Group, two probabilistic measures are calculated directly by the Markov model and they are the detection probability (DP) and failure probability that is used as a metric of technical difficulty (TF). Since the Markov model reflects the material flows and stocks inside a nuclear energy system, proliferation time (PT), a third PR measure, can also be calculated given a diversion rate. The material type (MT) is the fourth PR measure, which can be represented by an index based on the quality (physical and chemical composition) of material diverted. The material type also directly affects the proliferation cost (PC) and detection resources efficiency (DE); therefore, it is also used to represent these two PR measures.

THE MARKOV MODEL FOR PROLIFERATION STUDY OF THE ESFR SYSTEM

In this study, a hypothetical Example Sodium Fast Reactor (ESFR) system [1] is selected for exercising the Markov model approach that implements the PR&PP evaluation methodology.

The ESFR system includes four sodium-cooled 300 MWe reactors, fuel cycle facilities, and a deployment scenario, i.e., a co-location of the fuel cycle facility close to four reactor units [1]. The site also contains a spent fuel staging area used for washing spent fuel assemblies and transferring them to the fuel cycle facility. The fresh fuel is also transferred to the reactors via the staging area. In addition, a spent fuel storage area is provided for transfers from and to reactors. An external source of heavy metal makeup is required for the recycle facilities. It is assumed the external source of makeup is provided in the form of LWR spent fuel assemblies.

The recycling elements, which are the key elements of the ESFR system, are shown in Figure 1 together with the material flows. Also, some of the safeguards approaches associated with each element are sketched in Figure 1. Figure 2 is the Markov model of the overall ESFR system. The material flows of the ESFR system can be tracked from Figure 2, as the Markov model is created based on the flows inside the system. Details of fuel storage, transfer, and reactors can be found in [1, 2].

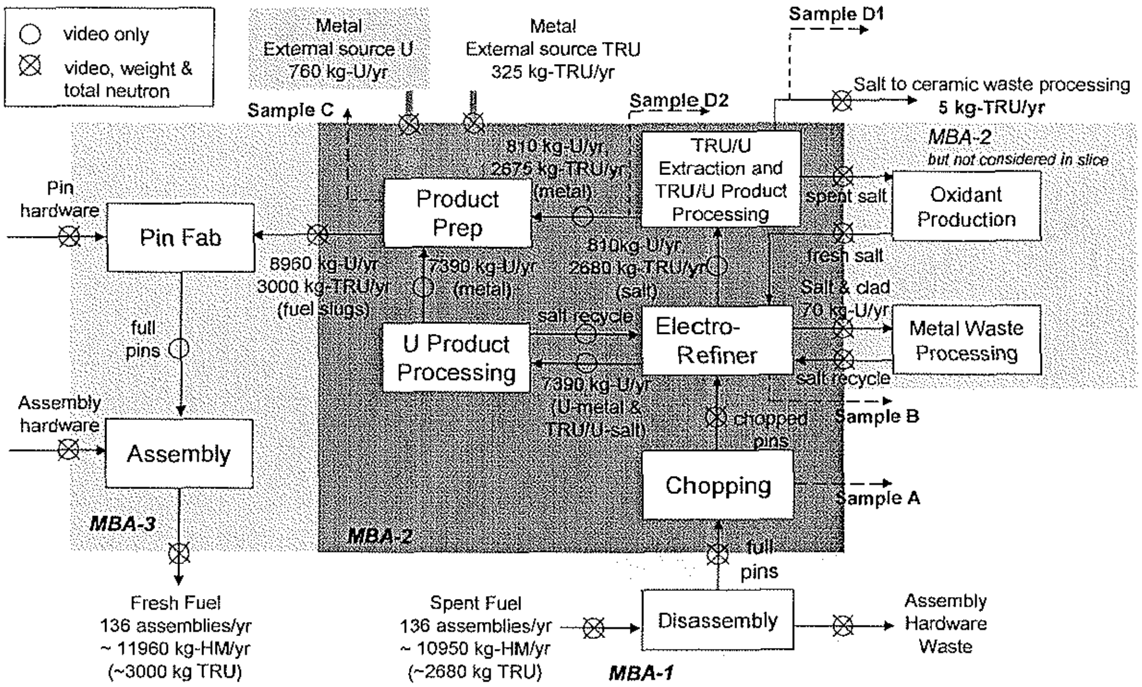

Figure 1: ESFR Recycling Elements and Related Safeguards

The role of the LWR related elements in Figure 2 is to provide external makeup source of TRU and U product to the element "Product Preparation." In Figure 2, Recycle Elements I and II reprocess the spent fuel to produce the mixed TRU and U fresh fuel that will be shipped back to the ESFR reactor (not shown in Figure 2). Recycle Element II-1.1 is simplified to provide external sources of U and TRU only. Recycle Element II-1.2 is actually the element "Disassembly" and it disassembles the ESFR spent fuel assemblies. Recycle Element I processes the bulk spent fuel electrochemically and produces the TRU and U, which will be used to fabricate fresh fuel pins and assemblies in Recycle Element II-2. Recycle Element I contains more elements, i.e., chopping, electro-refiner, U-product processing, TRU extraction, and product preparation, as shown in Figure 1. The new fuel (fresh fuel for the fast reactors) will be shipped from Recycle Element II-2 to the "SF & NF Storage Cell" (not shown in Figure 2). The waste output is not included in Figure 2.

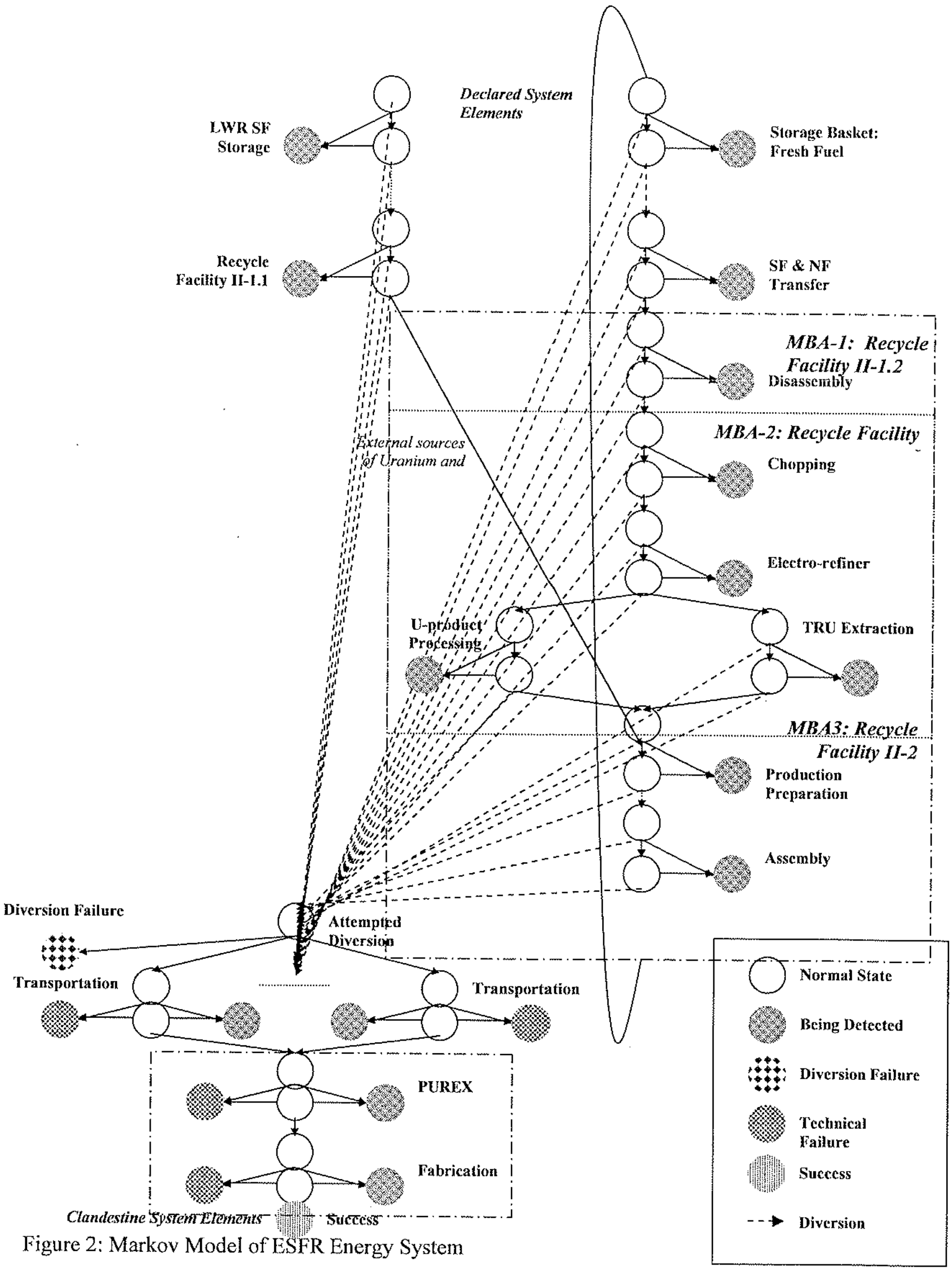

Figure 2: Markov Model of ESFR Energy System

From Figure 1, each year the inputs include 136 ESFR spent fuel assemblies (~10,950 kg-HM containing about 2,680 kg TRU) to element "Disassembly" and external sources of 760 kg uranium metal and 325 kg TRU metal to element "Product Preparation". The salt will be built-up during the reprocessing of chopped ESFR SF pins. The output of the ESFR slice is the 136 ESFR fresh fuel assemblies (~11,960 kg-HM containing about 3,000 kg TRU) per year. Some other material flow includes sampling at different elements and salt and clad processing.

Material balance areas are defined in both Figures 1 and 2. Strategic points including KMPs and the associated safeguards approaches can be established between two stages along the ESFR material flow diagram. Some of the safeguards are defined Figure 1. A more detailed description safeguards assigned to individual system elements can be found in [2].

The Markov model of the ESFR system shown in Figure 2 is illustrated in terms of a diversion. Potential paths for diversion are represented in dashed lines in Figure 2. It is assumed that a PUREX-like undeclared system element exists and reprocesses the diverted material by extracting pure plutonium and converting it into metal. There are five different types of states in the Markov model. The normal state indicates the normal operation of either a declared element or an undeclared element. The state of "Being Detected" indicates the detection of a diversion using the safeguards approaches. The state of "Diversion Failure" represents the failure of a diversion because the proliferator is not capable of overcoming the intrinsic barriers. Even after successful diversion of material into the undeclared elements, the proliferator may still fail and end up with the state of "Technical Failure" due to technical difficulties in the processing of the diverted material. The state of "Success" can be reached only if the proliferator overcomes all the safeguards, intrinsic barriers, and technical difficulties. States of "Being Detected", "Diversion Failure", and "Technical Failure" are all absorbing states, i.e., the diversion is over once the diversion is detected, or failed due to intrinsic barriers, or failed due to technical difficulties.

Given the initial status, the Markov model is characterized by a set of differential equations and can be solved numerically to obtain the states at any time. A Matlab-based software PRCALC has been developed to automatically create the Markov model that represents a specific scenario of an energy system and solve for both probabilistic and deterministic PR measures.

DIVERSION SCENARIOS OF THE ESFR SYSTEM

In this study, we evaluate PR measures of each ESFR system element by assuming that diversion occurs at only one system element at a time. It is assumed that diversion rates at different stages are all the same (2σ) [2]. The PR measures are computed using the PRCALC for each system element and the results are summarized in Table 1.

Columns 2 and 3 in Table 1 show the probabilities of detection (DP) and failure (PF) at the end of proliferation time (PT), which includes both the times to divert and reprocess 1SQ equivalent of Pu. Note that we use PF as a metric for the PR measure technical difficulty (TD) here. The material type column shows the MT value of material at each element. The MT values are calculated based on the physical forms and chemical compositions of material, as shown in [2]. Columns 6 and 7 give the numerical values of PR measures proliferation cost (PC) and detection resources efficiency (DE), which are basically the same as the MT values, as discussed in [2]. Larger PR measure values indicate that elements are more proliferation resistant. In Table 1, PS in column 8 represents proliferation success probability, which is not one of the PR measures. PS can be calculated directly from the Markov model of ESFR system. Finally, major safeguards for each stage are shown in Table 1.

Table 1: Detection and Success Probability for Each Stage

Stage	DP	PF	MT	PT	PC	DE	PS	Major Safeguards
I: LWR SF	0.96	0.038	0.4	292	0.4	0.4	0.003	3A, 1B, 1E, 1F, 4B, 4C
I: Storage Basket for Fresh Fuel	0.45	0.039	0.4	30.1	0.4	0.4	0.018	1B, 1D, 1G, 2A,
II: Transfer Port	0.98	0.013	0.5	146	0.5	0.5	0.007	3A, 1B, 1E, 1F, 4B, 4C
II: ESFR Reactor	0.69	0.048	0.5	60.2	0.5	0.5	0.0039	1B, 1D, 1G, 1H
III: Transfer	0.98	0.013	0.5	146	0.5	0.5	0.0066	3A, 1B, 1E, 1F, 4B, 4C
III: Storage Basket for Spent Fuel	0.31	0.06	0.5	60.2	0.5	0.5	0.0046	3A, 1B, 1E, 1F, 4B, 4C
IV: Transfer Port	0.44	0.114	0.5	22.6	0.5	0.5	0.017	3A, 1B, 1E, 1F, 4B, 4C
V: Transfer	0.41	0.054	0.5	45.2	0.5	0.5	0.009	3A, 1B, 1E, 1F, 4B, 4C
VI: Staging/Washing Area	0.43	0.055	0.5	45.2	0.5	0.5	0.0089	3A, 1B, 1E, 1F, 4B, 4C
VII: Transfer Port	0.55	0.14	0.5	22.6	0.5	0.5	0.022	3A, 1B, 1E, 1F, 4B, 4C
VIII: Transfer	0.53	0.069	0.5	45.2	0.5	0.5	0.011	3A, 1B, 1E, 1F, 4B, 4C
IX: SF & NF Storage Cell	0.63	0.16	0.5	22.6	0.5	0.5	0.027	3A, 1B, 1E, 1F, 4B, 4C
X: Transfer Port	0.57	0.037	0.5	30.1	0.5	0.5	0.0185	3A, 1B, 1E, 1F, 4B, 4C
XI: Transfer	0.59	0.033	0.5	30.1	0.5	0.5	0.017	3A, 1B, 1E, 1F, 4B, 4C
XII: Recycle Elements II-1.1	0.98	0.007	0.5	136.5	0.5	0.5	0.004	3A, 1B, 1E, 1F, 4B, 4C
ESFR SF Disassembly	0.68	0.023	0.5	30.1	0.5	0.5	0.011	1F, 2A, 3A, 3D, 4B
Chopping	0.78	0.018	0.5	30.1	0.5	0.5	0.009	1B, 1D, 1E, 3A, 3D, 3E
Electro-refiner	0.72	0.105	0.7	22	0.7	0.7	0.017	3A, 3D, 3E
U-product Processing	0.72	0.018	0.7	500	0.7	0.7	0.003	3A, 3D, 3E
TRU Extraction	0.41	0.058	0.3	23	0.3	0.3	0.009	3A, 3D, 3E, 1B, 1E, 2F
Product Preparation	0.64	0.260	0.4	45.2	0.4	0.4	0.0044	3A, 3D, 3E, 1E, 1F, 1G
Pin Fabrication	0.93	0.027	0.4	30.1	0.4	0.4	0.013	3A, 3D, 3E, 2A, 2F
Assembly	0.96	0.028	0.4	30.1	0.4	0.4	0.014	3A, 3D, 3E, 2A, 2F

As noted above, probability of proliferation success is not one of the PR measures but it certainly reflects proliferation resistance of the corresponding element with assumed safeguards and intrinsic barriers. The comparison between proliferation success probabilities can tell where safeguards and/or intrinsic barriers should be strengthened to make it more proliferation resistant. A bar diagram representation of the proliferation success probabilities at each system element defined in Table 1 is shown in Figure 3.

Assessment of proliferation resistance should not rely solely on one or some of measures, e.g., proliferation detection probability or failure probability (technical difficulty). Other measures shown in Table 1 should also play important roles in the PR evaluation of individual ESFR recycle elements. For the U-product Processing element, extremely long diversion time and unattractive material type make it also very proliferation resistant. The TRU Extraction element is less proliferation resistant because the material it contains is TRU metal, which is very attractive. In addition, the diversion time is very short and proliferation cost is low. It is also expected that more resources should be spent on detection due to the fact that the material is more attractive to a potential proliferator and the detection will be expensive.

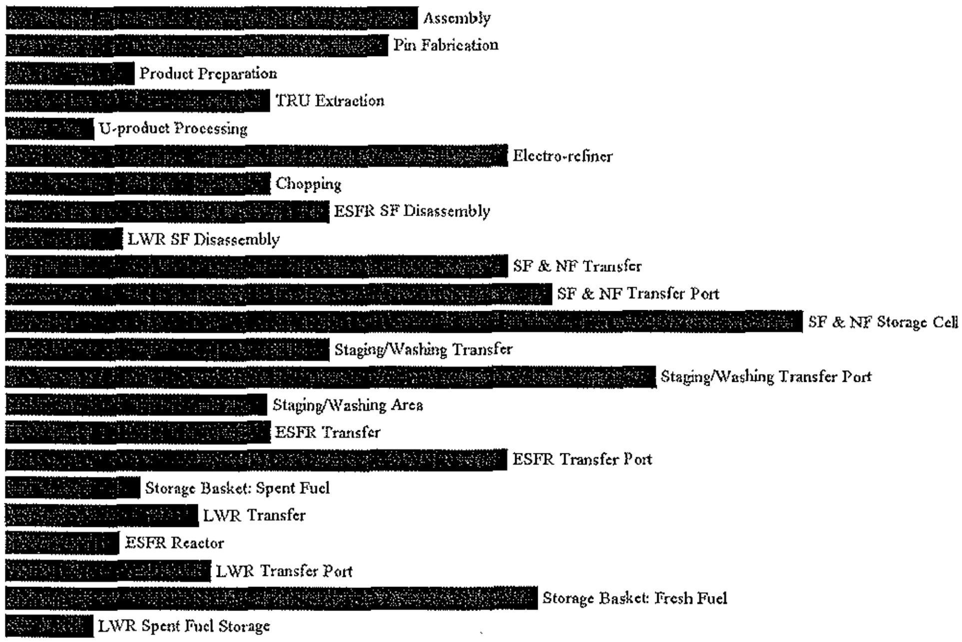

Figure 3: Bar Diagram Representation of Diversion Success Probabilities at ESFR System Elements

CONCLUSIONS AND FUTURE WORK

Using the Markov model approach, PR measures as well as success probabilities of diversion at individual ESFR system elements are computed. The results reflect PR characteristics of system elements and can provide useful information to system designers and to program policy makers.

The Markov model approach is highly adaptable and scaleable. It has been applied previously to evaluate both the PR&PP characteristics of various nuclear energy systems and different threats posed to these systems including misuse, diversion, theft, and sabotage, as presented in [2-5].

It is recognized that modeling impacts of these relevant features in a precise manner is very difficult. In the Markov modeling of nuclear energy systems, mathematical representations of these features can be formulated such that at least the trend of the corresponding impacts and the boundary conditions of the impacts, i.e., with and without a specific feature, can be captured using the introduced. Therefore, the numbers and conclusions presented here should not be taken as absolute predictions. Instead, these are considered as outcomes of the assumptions used in the Markov models. The Markov models and parameters in this study are both preliminary. The models need to be refined and parameters need to be further developed and validated.

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REFERENCES

[1] PR&PP Evaluation Methodology Expert Group, "Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems," Revision 5, September 30, 2006, available online at http://www.gen-4.org/Technology/horizontal/PRPPEM.pdf.

[2] M. Yue, L. Cheng, and R. A. Bari, "A Markov Model Approach to Proliferation Resistance Assessment of Nuclear Energy Systems," *Nuclear Technology*, **162**, 26, 2008.

[3] M. Yue, L. Cheng, I. A. Papazoglou, M. A. Azarm, and R. A. Bari, "Calculations of Proliferation Resistance for Generation III Nuclear Energy Systems," *Proceedings of the Global 2005 International Conference of Nuclear Energy System for Future Generation and Global Sustainability*, Japan, 2005.

[4] M. Yue, L. Cheng, and R. A. Bari, "Markov Methodology for Proliferation Resistance of Nuclear Energy Systems," *Proceedings of 29th European Safety, Reliability & Data Association (ESReDA) Seminar: Systems Analysis for a More Secure World*, Ispra, Italy, 2005.

[5] M. Yue, L. Cheng, and R. A. Bari, "Quantitative Assessment of Probabilistic Measures for Proliferation Resistance," *Transactions of American Nuclear Society*, **93,** 333, 2005.